Options for Renewable Natural Gas (RNG) in a Low-Carbon Future

Processing Methods for Large Scale Conversion of Seaweed to Energy-Relevant Products

November 16

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Natural gas use today

US uses 32 quad natural gas, emits 2.1 B ton CO_2

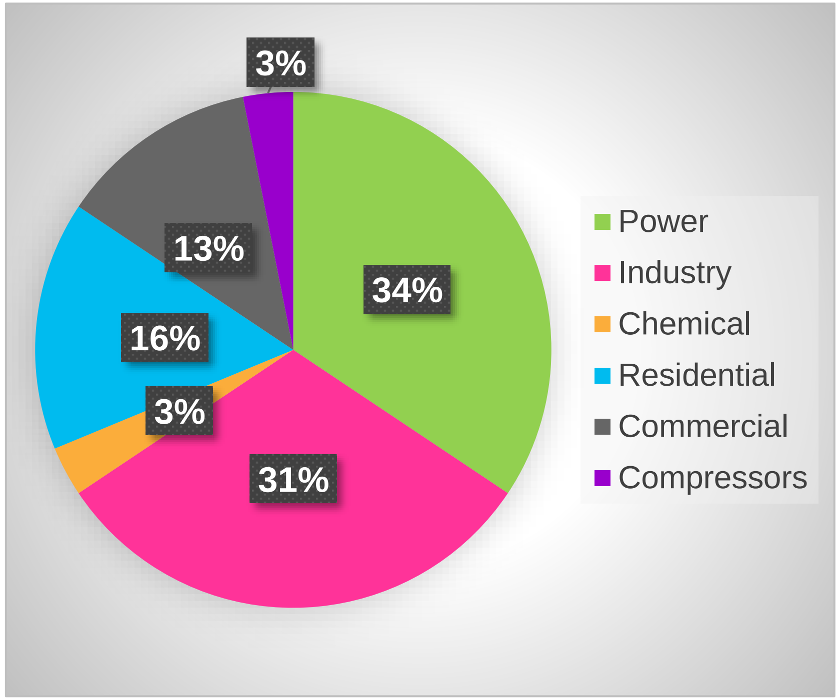
- 11 quads Power Generation
- 10 quad Industrial
- 1 quad for Chemicals

Large, constant loads served by interstate pipelines

- 9 quad Residential/ Commercial, primarily for heat

Small, seasonal loads served by gas utilities

- 1 quad Parasitic load – compressors



Best Fit for RNG: Decarbonizing Res/Com Segment

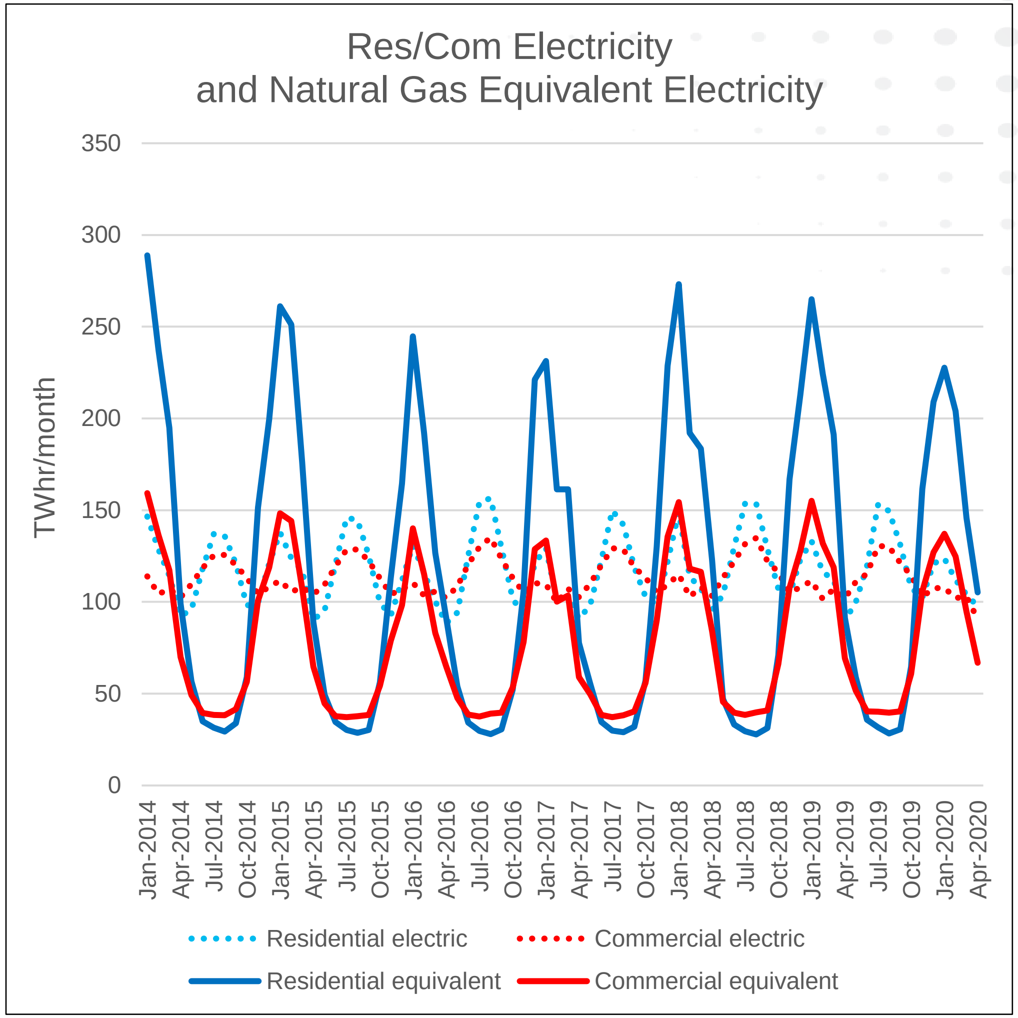
Current	Delivery point	$/MMBtu	$/MWhr
Natural Gas	Henry Hub	2.57	9
	Power Plant	2.98	10
	Industrial	3.85	13
	Commercial	7.28	25
	Residential	12.80	44
Electricity	Power Plant	19.42	61
	Industrial	21.65	68
	Commercial	31.06	106
	Residential	41.38	130

- Res/Com will be the most expensive sector to decarbonize
- Res/Com already pays the highest price for delivered energy
  - Electricity 3-4X cost of gas
  - Alternatively, there's a lot "space" to pay more for RNG
- Electrification requires massive expansion of electric generation, T&D, and retrofitting 75 MM homes and businesses
- Replacing fossil gas with renewable gas requires massive expansion of RNG production

CHANGING WHAT'S POSSIBLE

Electrification Challenge: CAPEX for Supply Chain

- Adding thermal load will require major expansion of Res/Com T&D
  - Electric grid winter peaks increase 2-3X
  - >2X expansion of electric T&D
  - T&D costs amplified by < 50% utilization
  - Need to upgrade service and replace gas appliances for 75 MM customers
- Conversions are expensive, disruptive, and difficult to execute
  - "Death spiral" for unconverted customers
- Res/Com electric grid also targeted for vehicle electrification
  - Demand potentially larger than thermal peak



RNG: Can Afford to Pay More, but Need New Sources

- US uses 32 quads of gas; Res/Com 9 quads
- ~1-3 quads RNG from "Traditional" sources (manure, wastewater, landfill)
- ~5 quads (max) from sustainable biomass (wood, energy crops)
- Power-to-Gas (P2G) limited only by cost

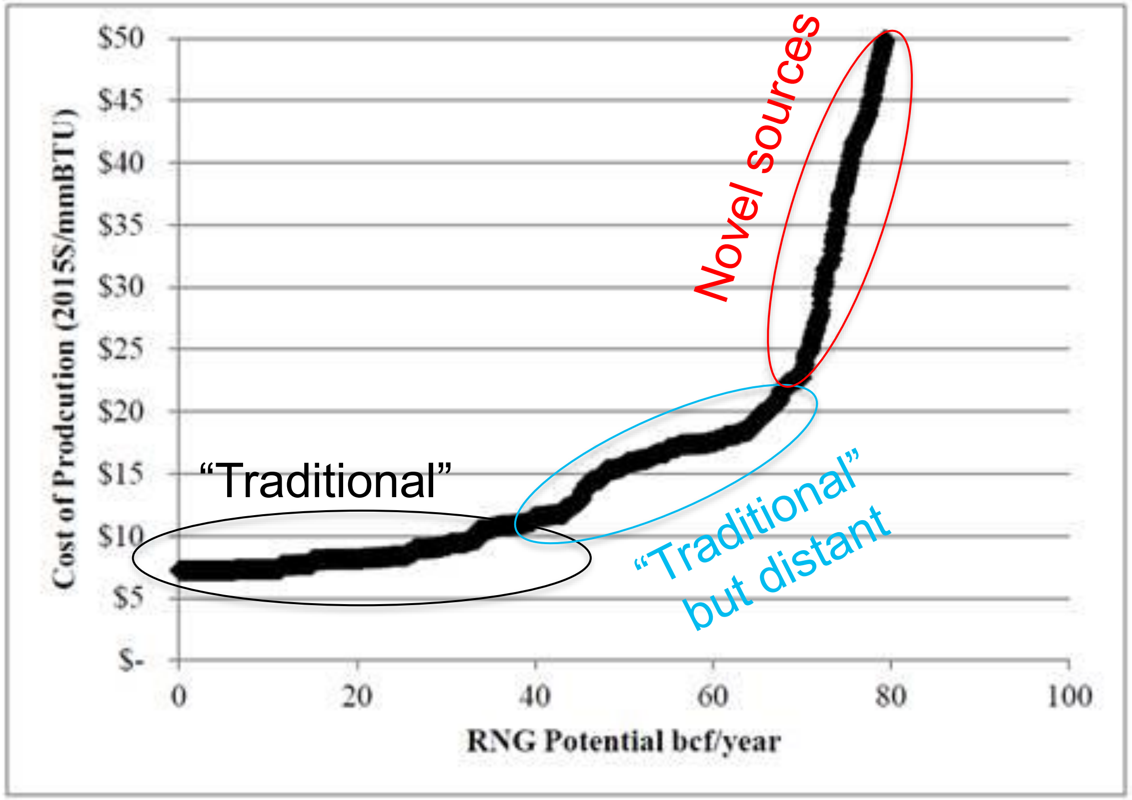


Figure 29. Combined source supply curve of RNG

- RNG Cost curve - California

Renewable feedstock competitors

- Competitive line-up
  - Seaweed
  - Biogas (manure, wastewater, landfills)
  - Wood
  - FOGs (fats, oil, grease)
  - Electricity (Power-to-Gas; Power-to-X)
  - Fossil natural gas
    - With DAC (net zero carbon for all applications)
    - With CCS (net zero carbon for power generation)
- Issues
  - Cost
  - Availability
  - Transport-ability
  - Store-ability
  - Community license to operate

RNG Sources and Economics - Traditional

Feed	Feed Cost ($/MMBtu)	Process	RNG production ($/MMBtu)	Issues
Dairy manure	"free" manure, sometimes has negative value	AD/membrane/ compressor	$8-30	Scale – typically small. 1000 cows = 40K scfd. Distant from population, gas infrastructure Economical due to low CI
Wastewater treatment gas	"free" raw gas, unless used in boilers	2-stage clean-up/ compressor	$6-10	Few plants at ~1MM SCFD scale; near population
Landfill gas	"free" raw gas – regulations require collection	Multi-train clean-up/ compressor	$6-15 @ 2MM SCFD	Need large scale to be economic

RNG Sources and Economics – “Novel”

Feed	Feed Cost ($/MMBtu)	Process	Processing cost ($/MMBtu)	Issues
Seaweed	$100/dry ton = $9/MMBtu	Assume same as dairy?	$15-50 Assume production costs same as dairy?	Scale Location: proximity to population and gas infrastructure Thermal balance for digester
Wood	$5-10/MM Btu	Gasification	$13-15	Scale: 900 tpd wood, 8MMSCFD
Renewable electricity + DAC		Power-to-gas	$25+	2030 estimate
Fossil gas with DAC	$4 (interstate pipeline delivery)	DAC:$50-250/ton CO2	$4+ $3.4 = $7.4 $4 + 17 = $21	Acceptable to continue burning fossil fuel?
Fossil gas with CCS	$4 (interstate pipeline delivery)	CCS: $100/ton CO2	$4 + $6.8 = $11	Relevant for power gen only

CHANGING WHAT'S POSSIBLE

Reality Check: 80% GHG Reduction CA by 2050

Energy+Environmental Economics (2015) bottom-up analysis Pathways (v.2.1)

- Electrification scenario, where all energy end uses, to the extent feasible, are electrified and powered by renewable electricity by 2050;
- Mixed scenario, where both electricity and decarbonized gas play significant roles in California's energy supply by 2050
- Parity within error of model:
- Renewable CH_4 in 2050
  $20-25/MMBtu Anaerobic digester
  $30-138/MMBtu Electrolysis +
  methanation + DAC
- Renewable H_2 in 2050
  $24-112/MMBtu Electrolysis
  limited to 20% concentration in pipeline
- Gas demand unchanged from reference (do nothing) case, but fossil gas <10%, RNG >80%, balance CH_4 and H_2 from electrolysis

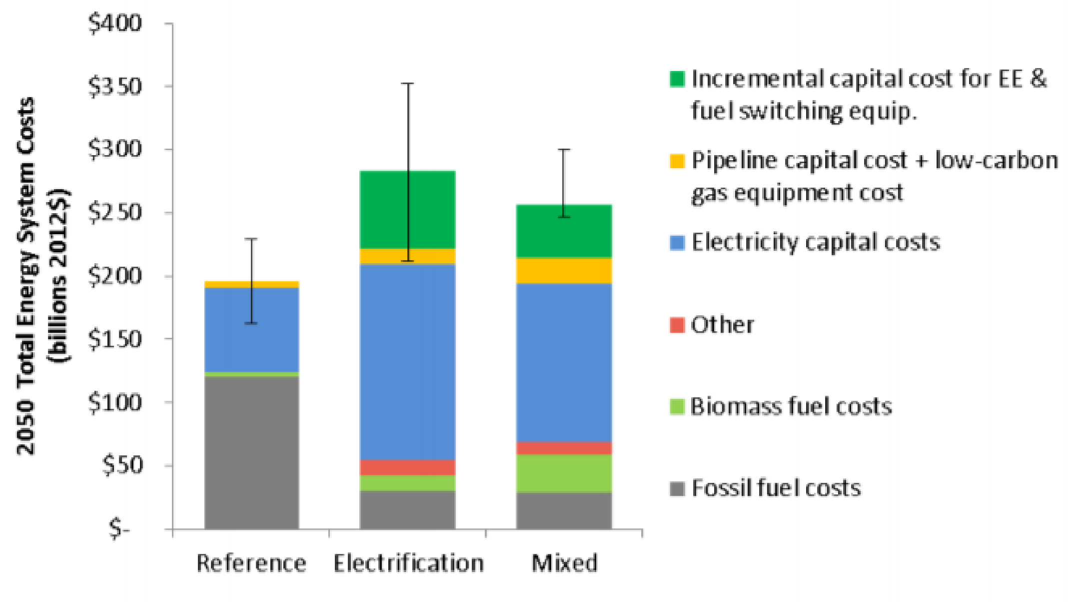


Figure 10. 2050 total energy system cost by scenario (levelized cost of fuel and levelized capital cost of energy infrastructure)

Conclusions

- RNG's best fit is decarbonizing Res/Com sector
  - but role will be limited if it's ok to burn fossil gas and compensate with DAC

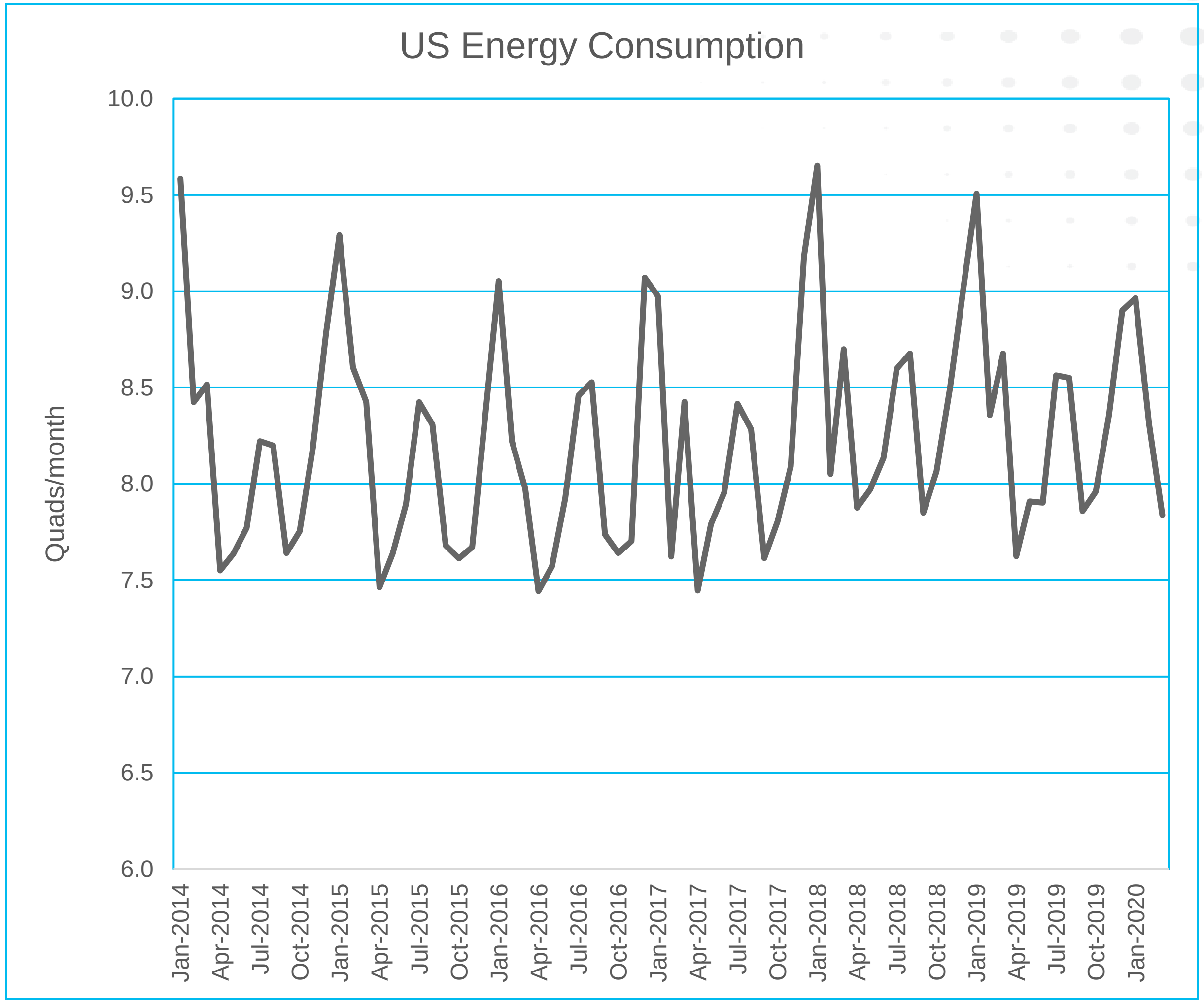
- RNG needs new sources
  - Possibly wood, seaweed, P2G

- To compete, novel feedstocks need to:
  - Beat Res/Com heating electrification
  - Reduce feedstock cost, minimize logistics/transportation,
  - If using digester, needs to be thermally neutral or positive
  - Be at scale, >100,000 scfd
  - Have carbon selectivity to methane > 50%
    - Possibly upgrade waste CO_2 to methane?
  - Get built close to population centers and existing gas infrastructure

Manage Supply/Demand Swings

Need long-term storage and large-scale transmission

- Res/Com thermal loads drive annual energy swings
  - Major winter heating peaks
  - Minor summer cooling loads
- Renewable generation peaks not in sync with demand
- Natural gas storage balances supply/demand for thermal and electric loads today
- Best renewable resources not near population centers, and



Factors in End Users' Energy Cost

- Energy cost

- Transmission, Distribution, Storage
  - Regulated energy systems designed to meet peak load, often few hours/year
  - Electric grid: peak + 10-20% reserves
  - Gas grid: "design day" (coldest temp)
  - Northern electric and gas utilities are both winter-peaking
  - Southern utilities seeing increases in summer peaks

- End Use Appliance Cost
  - Replacement costs
  - Service upgrades

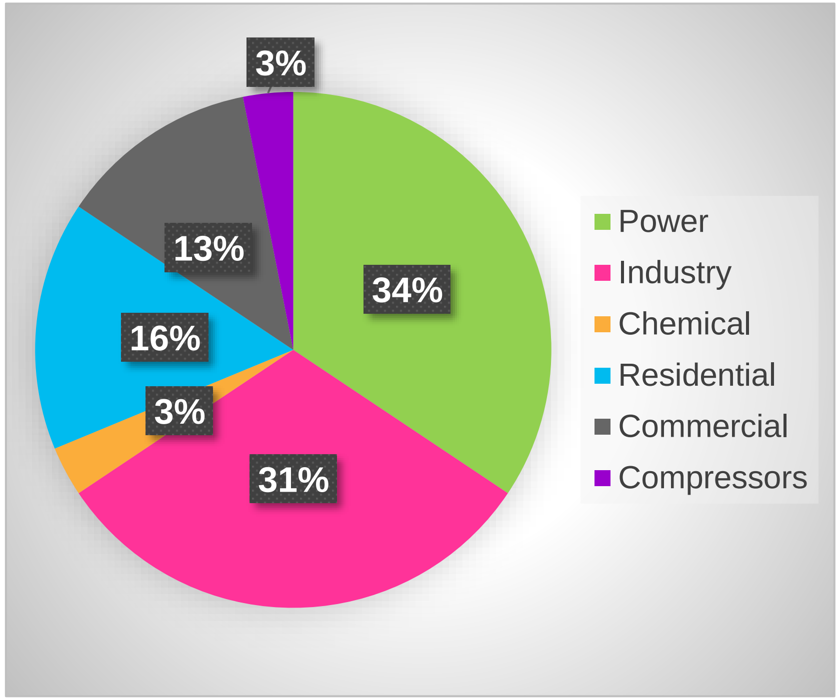
Why RNG: Natural gas use today

US uses 32 quad natural gas, emits 2.1 B ton CO_2

- 11 quads Power Generation, 1580 TWhr electricity
- 10 quad Industrial
  - 3 quad combined heat/power, 500 TWhr
  - 7 quad heat
- 9 quad Res/Com for heat
- 1 quad for Chemicals
- 1 quad Parasitic load – compressors

14 quad power

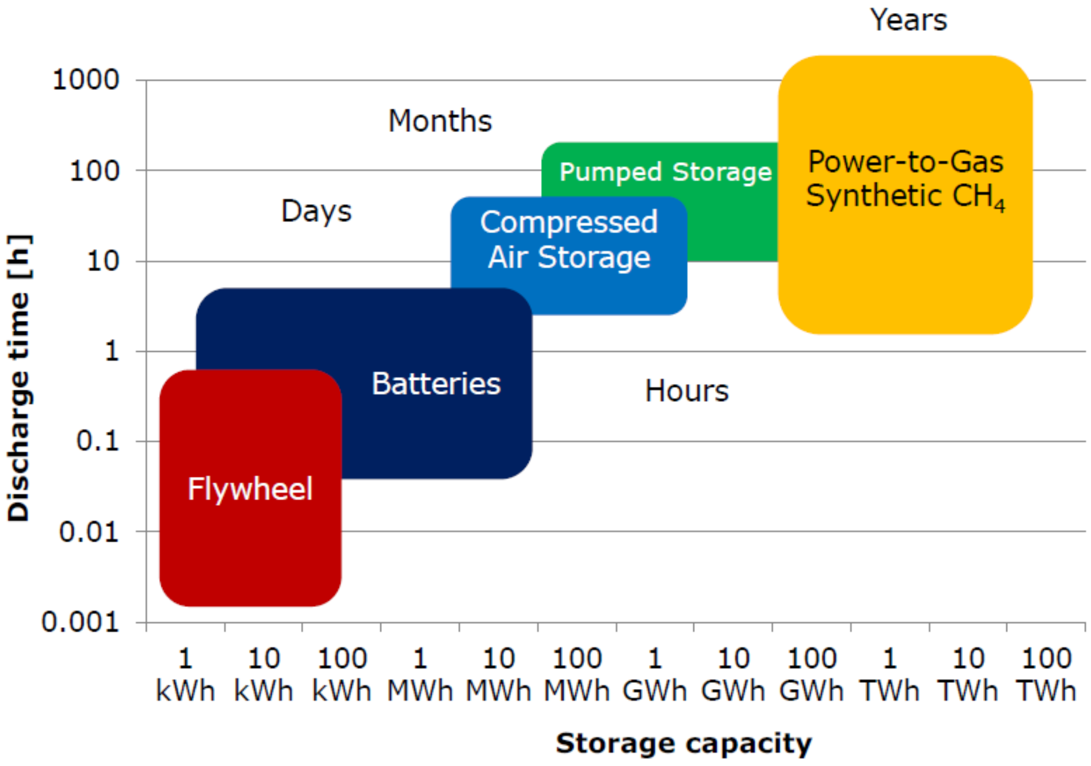
16 quad heat



CHANGING WHAT'S POSSIBLE

Gas Grid for Large Scale Energy Storage/Transmission

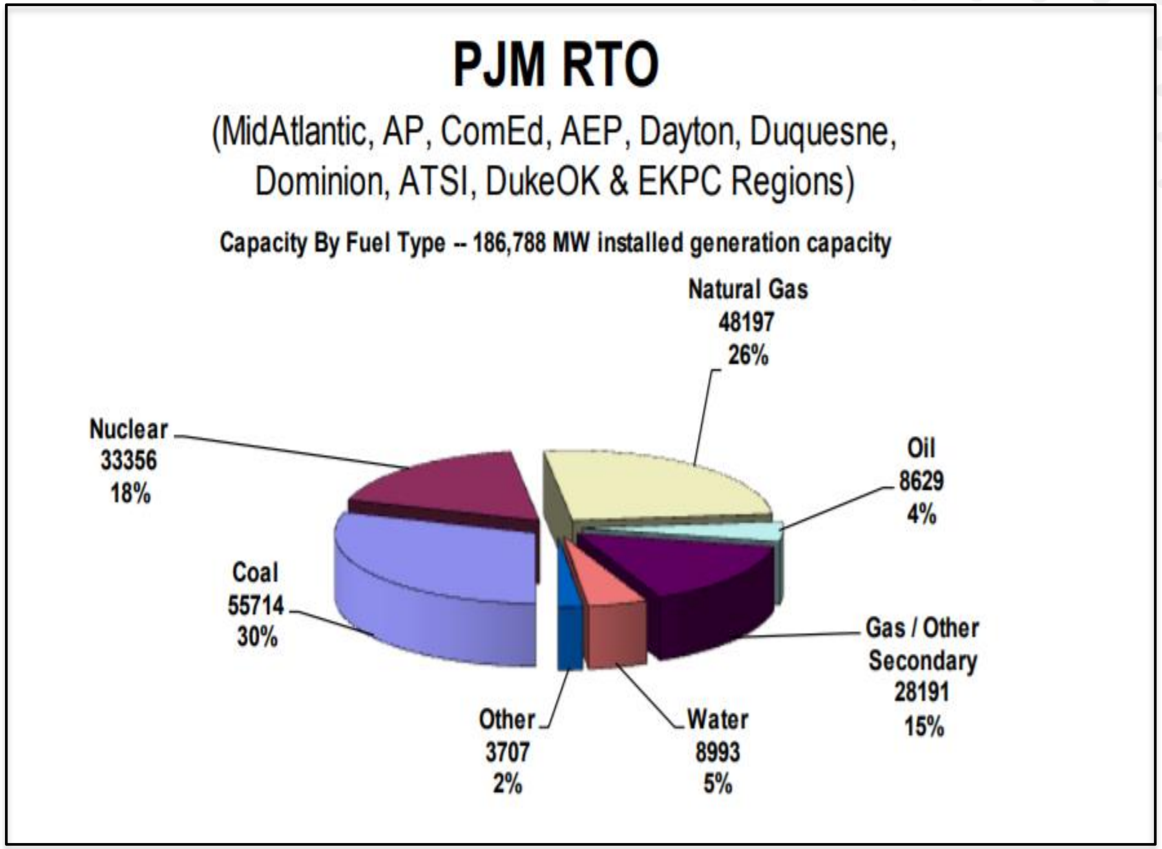
- US NG storage capacity 4.8 quad/830 TWhr
  - $83 T CAPEX for Li battery @$100/kw-hr
  - Infrastructure in place
  - Zero self-discharge
  - Gas storage costs <$1/kW-hr for a year of storage
- Gas transmission
  - >250,000 miles high-pressure gas transmission
  - 42” pipeline carries ~40 GW(thermal) for 2500 miles with ~2% parasitic load for compressors
  - 765 kV transmission line carries 2.3 GW(electric) for 300 miles with ~1.5% power loss
  - Cost to move gas 2500 miles ~$1.5/MMBtu
- CH_4 preferred for Res/Com thermal load



Electricity Generation: Green Gas vs CCS vs All Renewables

NETL Cost and Performance Baseline for Fossil Plants

- NGCC/CCS vs NGCC with Green Gas
  - CCS adds ~$31.1/MW-hr to NGCC LCOE
    - Base case gas cost $4.42/MMBtu
    - Parity GG cost $9.31/MMBtu
  - Coal/CCS vs with NGCC Green Gas
    - Subcritical coal/CCS $116/MW-hr
    - Supercritical coal/CCS $114/MW-hr
    - Parity CC cost $15.80/MMBtu
  - No infrastructure investment required for Renewable CH_4 - drop-in fuel in NGCC



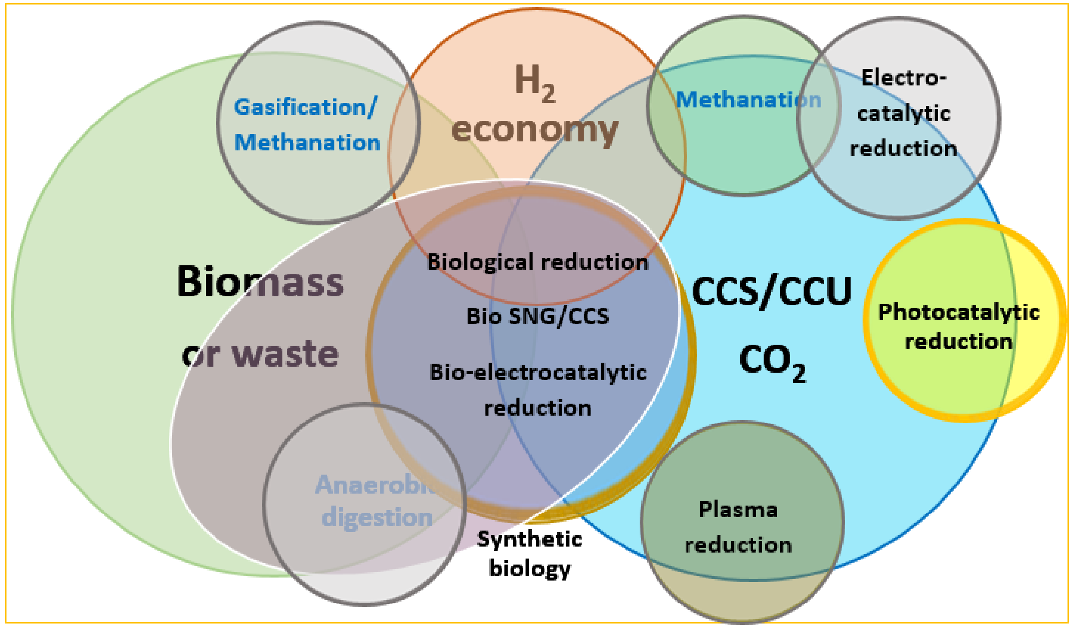
Green Gas Production in the Energy Landscape

“Feeds” intersect with:

- Biomass-to-energy (~5 quad carbon limitation)
- H_2 Economy
- Carbon Capture/Utilization (“unlimited” carbon)
- Zero-carbon electricity

Applications intersect with:

- Res/Com/Industrial/Power Gen/Transportation applications for natural gas and hydrogen
- Decarbonizing the gas grid
- Power-to-Gas (P2G)
- Energy storage, integration of renewables in the electric grid
- Maximizing carbon yield for biofuels and chemicals



Processes intersect with:

- Anaerobic digestion, biomasss gasification, synthetic biology, electrobiology
- H_2 production - nuclear/thermal, electrochemical, methane pyrolysis
- CO_2 conversion – biological, catalytic, electrochemical, photochemical

Bracketing Solutions

Option	NG grid mix/flow Quad/(Bft^3/hr)	New pipes	CCS MM ton/yr)	Electric generation/ storage	Electric T&D	End user	CO2
Base case	32 Q Fossil 4 Bft^3/hr	0	0	100 GW wind, 100 GW nuke 450 GW natural gas 1000 GW total	5.5. MM miles T&D 4100 TWhr	No Change	2.2 B ton/yr
1: Use existing technology Maximize use of biogas (0.4 Q) + biomass (1 B ton, 10 Q) Replace gas power with renewables	6 Q RNG 15 Q Fossil 3 Bft^3/hr	0	0	450 GW wind + >3 TWhr storage Or 200 GW nuclear + <2 TWhr storage	No Change	No Change	2.8 B ton/yr
2a: 1+ CCS on gas-fired power	6 Q RNG 26 Q Fossil 4 Bft^3/hr	1.4 Bft^3/hr CO2 grid	800	No Change	No Change	No Change	1B ton/yr
2b: 1+ replace gas power with renewables	6 Q RNG 15 Q Fossil 3 Bft^3/hr		No Change		No Change	No Change	1B ton/yr

Bracketing Solutions – Assume CCS for NG-fired electricity

Option	NG grid mix/flow Quad/(Bft^3/hr)	New pipes (Bft^3/hr)	CCS	Additional Electric generation/ storage	Electric T&D	End user	CO2 MMTon /yr
3: 1 + 2a + electrify everything else	6 Q RNG 11 Q Fossil 2 Bft^3/hr	1.4 Bft^3/hr CO2 grid	800 MM ton/yr	1400 GW wind >3 TWhr storage or 600 GW nuke + >2TWhr storage	Increase peak capacity >3X for winter-peaking utilities	Convert 70% of 80 MM Res/Com customers to electricity	0
3: 1 + 2a + H2 with load-following electrolysis located at power plants	6 Q RNG 11 Q Fossil 2 Bft^3/hr	1.4 Bft^3/hr CO2 grid + 5.6 Bft^3/hr H2 grid	800 MM ton/yr	1700 GW wind or 750 GW nuke	No change	Convert 70% of 80 MM Res/Com customers to H2	0
3: 1 + 2a + CH4 with load-following electrolysis located at power plants	6 Q RNG 11 Q Fossil 15 Q e-CH4 4 $BBft^3$/hr	3.3 Bft^3/hr CO2 grid	800 MM ton/yr + 1100 MM ton/yr DAC for e-CH4	>2000 GW wind or >1000 GW nuke	No change	No change	0